Measurements and Modeling Comparisons of Underwater Communications Performance at three Shallow-Water Sites

Martin Siderius, Michael B. Porter and Paul Hursky
Science Applications International Corporation
10260 Campus Point Dr.
San Diego, CA 92121
Vincent K. McDonald
Space and Naval Warfare Systems Center
San Diego, CA

***Abstract* – Large differences in performance of underwater acoustic communications were found when looking at results from three shallow water sites. Using acoustic modeling, these channel responses are simulated and communications performance predictions are made. Ray based modeling is used to determine the mechanisms in the environment causing differences in bit error rates. Experimental results for the non-coherent Multi-Frequency Shift Keying (MFSK) signaling method showed better performance in very shallow water (about 5 m) with a lossy seabed compared to deeper water (about 80-150 m) with a more reflective seabed. The modeling shows that while interfering multi-path is an important mechanism for bit errors in the deeper water sites, the performance at the shallow water site depends mainly on the surface roughness, volume attenuation and ambient noise level. In this paper, simple acoustic modeling is used to capture the most important channel characteristics. The emphasis is on modeling the mulitpath arrival pattern and on the comparison between modeled and measured communications performance.**

I. INTRODUCTION

The need for reliable underwater communications is becoming apparent as applications increase for autonomous underwater vehicles and instrumentation. However, performance can be unpredictable, varying drastically depending on location, time-of-year and weather. In shallow-water channels the acoustics have many interactions with the boundaries and properties of the sea-surface and seabed will determine the extent and characteristics of the multipath. In some cases, performance is dominated simply by the signal-to-noise ratio while in others it depends mostly on the multipath interference. To combat this unpredictability, some underwater communications systems are designed for reliability even when operating in harsh conditions and these configurations lead to sub-optimal performance when good propagation conditions exist. Part of the challenge in optimizing performance is to predict which environmental factors have the greatest impact. A key element to predicting channel characteristics is correctly estimate the multipath and this is possible only if the properties of the boundaries are carefully modeled with simulation tools.

Good underwater acoustic modeling tools are available since the SONAR community has been interested in performance prediction for many years. However, the techniques appropriate for SONAR modeling are not always adequate for simulating a communications channel. The description of the environment (e.g. seabed type, boundary roughness, volume absorption) and its temporal variability should be appropriate for the space and time scales needed for realistic simulations of communication signals. As an example, formulae have been developed for low frequency SONAR to treat the loss associated with rough, time evolving, sea-surfaces. SONAR systems often have a relatively long integration time (order seconds), however, for communications, the symbol duration is the relevant time scale and this will likely be short enough to consider the surface as rough but frozen. The frozen sea-surface will scatter energy but the short time scales will reduce the amount of loss caused by long integration times. Therefore, new approaches (and formulae) suitable for the communications application should be used in simulation.

In recent years, advances have been made in using physics based, propagation modeling to simulate the channel impulse response and communications performance [1]. In addition, many experimental results on communications performance have been reported and an overview is given of these and the current state of underwater communications in Ref. [2]. However, very few experiments with simultaneous acoustic and environmental measurements have been made. These types of measurements are necessary for modeling with physics based approaches (as opposed to modeling by randomizing the phase of a few straight ray path arrivals). In this paper, the observed differences between experimental data are explained mainly by differences in multipath and this is illustrated with physics based simulations. In general, multipath plays an important role in performance so it is extremely important to validate model results with measurements at different sites to determine if performance prediction can be made when environmental conditions and source/receiver geometries change.

In this paper, three sites are considered for model/measurement comparisons. The approach is to use

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **01 SEP 2003**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**

4. TITLE AND SUBTITLE **Measurements and Modeling Comparisons of Underwater Communications Performance at three Shallow-Water Sites**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Science Applications International Corporation 10260 Campus Point Dr. San Diego, CA 92121**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR’S ACRONYM(S) 11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM002146. Oceans 2003 MTS/IEEE Conference, held in San Diego, California on September 22-26, 2003. U.S. Government or Federal Purpose Rights License., The original document contains color images.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**UU**	**7**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

both measured acoustic and environmental data to fine-tune the model before simulating communication signals. This technique of acoustically probing the channel followed by modeling is a practical way to predict performance. This could be used, for example, to optimize a network lay-down pattern or to predict where an autonomous vehicle will have a reliable link. Multi-Frequency Shift Keying (MFSK) is the signaling scheme used throughout the analysis in this paper. This is a non-coherent method since only the magnitude of the pressure field (not the phase) determines the transmitted symbol. The MFSK method is typically more robust than coherent schemes but uses bandwidth less efficiently. However, the simple nature of MFSK signaling makes it easy to analyze the impact of the channel physics on bit errors.

II. SHALLOW WATER EXPERIMENTS

The SignalEx series of experiments were designed to measure many different communications signaling methods in a variety of shallow water locations while simultaneously characterizing the environment. In addition to the actual communications signals, acoustic probes were transmitted to characterize the channel impulse response. Three of most recent experiments will be discussed in this paper. The first site is labeled SX-E and the other two of these sites are in the SX-F area shown in Fig.1.

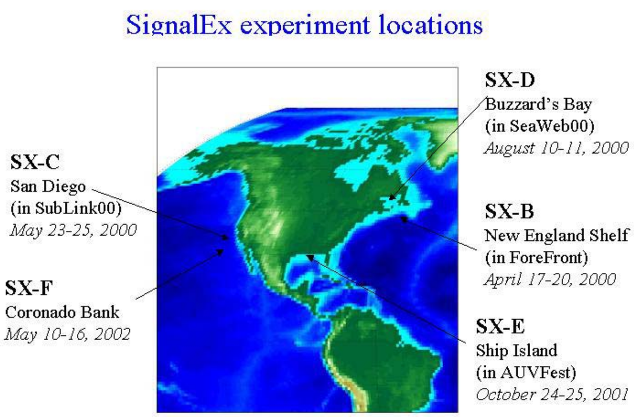

Fig. 1: Locations of the SignalEx experiments. SX-E and two sites in the SX-F experiments are considered here.

A. The SignalEx-E Ship Island Environment

The SignalEx-E experiment was near Ship Island in the Gulf of Mexico and took place October 24-25, 2001. The experiment was in an area of very shallow water (4-5 m) with little variation in water depth over the measurement area. A self-recording acoustic receiver system was deployed at 30^o 20.173 N 88^o 53.573 W. A sediment map indicated the seabed properties in the area have a mean grain size of about 6.0 ϕ which is classified as a sandy mud with a water column seabed sound speed ratio of 0.9873 (about 1481 m/s). This type of seabed is fairly lossy, (i.e. not very reflective to acoustics). Several conductivity, salinity and depth (CTD) measurements were taken and converted to sound speed and these showed the profile was nearly constant in depth as the water column appeared to have been mixed due to moderately windy conditions before and during the experiment. A sample sound speed profile is shown in Fig. 2.

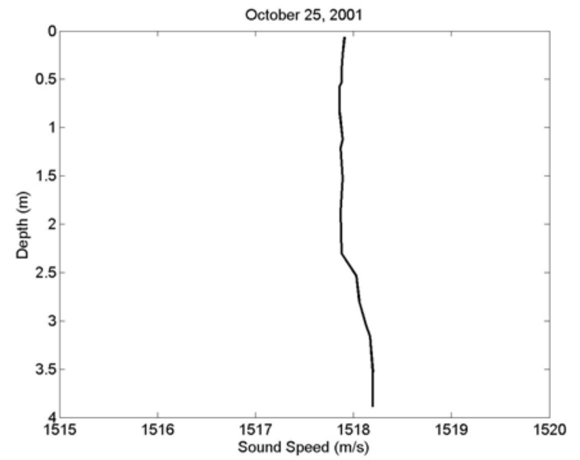

Fig. 2. Measured sound speed profile for SX-E Ship Island site in the Gulf of Mexico on October 25, 2001.

B. The SignalEx-F La Jolla Environment

The first experiment of SX-F took place on May 10, 2002 (referred to as the La Jolla experiment). The same acoustic receiving equipment was deployed in 80-m water depth at 32^o 46.562 N 117^o 20.459 W and the acoustic track was approximately along the 80-m iso-bath. Sediment maps show the La Jolla site to have a sand/silt surficial layer with grain sizes of 4-5 ϕ (or sound speed ratio of 1.0364-1.0179 or 1527-1555 m/s calculated using formulas in Ref. [3]). CTD casts were taken and the sound speed profile in the water column computed and is shown in Fig. 3.

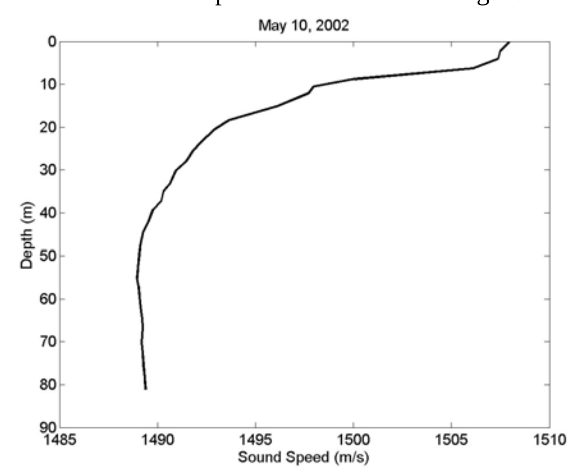

Fig. 3. Measured sound speed profile for SX-F site off the coast of San Diego on May 10, 2002.

C. The SignalEx-F Coronado Bank Environment

The Coronado Bank experiment of SX-F took place on May 16, 2002. The acoustic receiver system and source track were located along an iso-bath of about 150 m. The water column sound speed profile was roughly the same as for the May 10, 2002 La Jolla experiment shown in Fig.3.

The sediment charts show a more reflective material for the surficial layers corresponding to rock and gravel with some course sand. This translates into grain sizes less than about 2 ϕ or sound speeds greater than about 1700 m/s.

D. Acoustic Measurements

The experimental setup was similar for all the experiments (SX-E and both experiments in SX-F). An autonomous transmit and receive system (called a telesonar testbed) was deployed on the seabed with receiving hydrophones suspended a few meters above the sea floor using a sub-surface float. A detailed description of the telesonar testbeds can be found in Refs. [4,5]. A second telesonar testbed acted as the transmitter and was deployed over the side of a drifting ship. Each of the experiments lasted a few hours during which the distance between the source and receiver telesonar testbeds increased from about 500 m to 7 km. For the very shallow SX-E experiment the drifting source was kept near mid-water (about 2-m depth). For the SX-F tests, the source was maintained at about 20-m depth.

Within 20 s of each minute a set of 50, 50 ms, 8-16 kHz linear frequency modulated (LFM) probe signals were transmitted. These probe signals were matched filtered and the envelope amplitudes were averaged to produce a single, representative impulse response for each minute. For display purposes, the travel times have been removed and the impulse responses are shown on a reduced time scale (x-axis) and range from the source (y-axis). The measured impulse responses comparing Ship Island and the La Jolla sites are shown in Fig. 4. Note, in Fig. 4, that the Ship Island impulse response shows no resolvable multipath structure (i.e. appears like a single arrival) while the La Jolla site shows several arrivals coming in around 50 ms after the first arrival. Also, the La Jolla impulse responses are not perfectly aligned after removing an assumed travel time- this is an indication that for longer ranges there is no direct path between source and receiver.

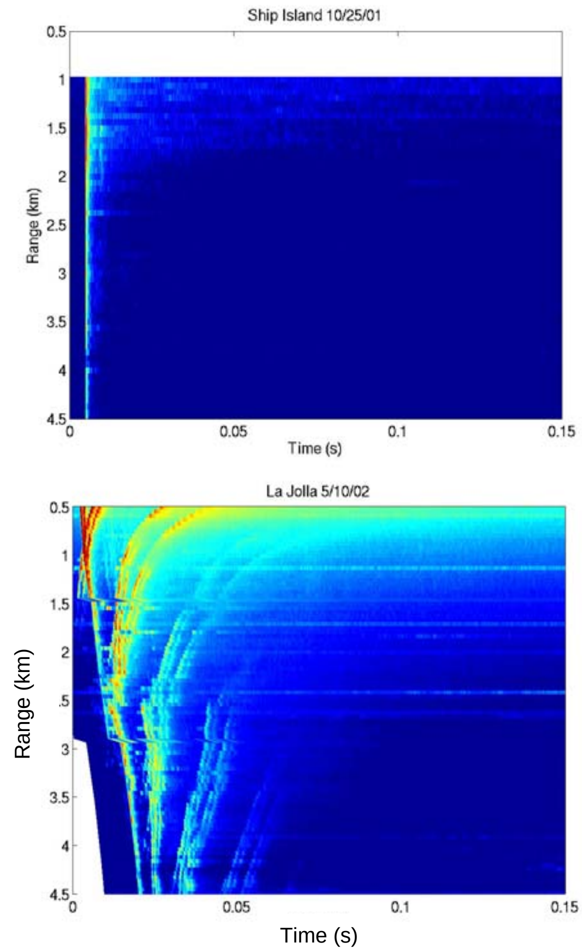

Fig. 4. Impulse response envelopes for SX-E and SX-F sites. Top panel shows results for SX-E Ship Island, lower panel is for SX-F La Jolla (no transmissions were recorded for Ship Island closer than 1-km)

III. MFSK COMMUNICATIONS SIGNALS

MFSK signaling is considered both simple and robust and for that reason it is commonly used in commercially available modems. The robust nature of the MFSK signals makes it useful to compare data rate and bit error performance against other (e.g. coherent) signaling schemes. In the SignalEx-E and F experiments, one minute every ½ hour was dedicated to MFSK signals. The MFSK used 128 frequency components spaced 40 Hz apart from 8 kHz up to 13.2 kHz. The upper and lower 4 tones are reserved for pilot tones to compensate for Doppler. The information is passed using a subset of the 128 frequencies that can be modified every 25 msec. One detail of the modulation scheme is the use of ‘1 of 4’ coding. This means 4 tones are used to encode 2 bits of data. The advantage of this is that in decoding, only a decision about which of the 4 tones is loudest is needed to determine if the transmission is a 0-0, 0-1, 1-0 or 1-1. This method is less problematic than having the decoder decide if a tone is a 1 (on) or 0 (off). Based on the frequency band used here, the maximum data rate is 60 bits in 0.25 ms, or 2400 bits

per second (bps). To transmit at lower data rates, the time duration of the tones is increased (e.g. 1200 bps is achieved by holding the tones on for 50 ms). In Fig. 5, a sample of the transmission pattern is shown for a 2400 bps MFSK transmission. In Fig. 5 the black regions indicate the tone is transmitting at full available power level and white regions are off.

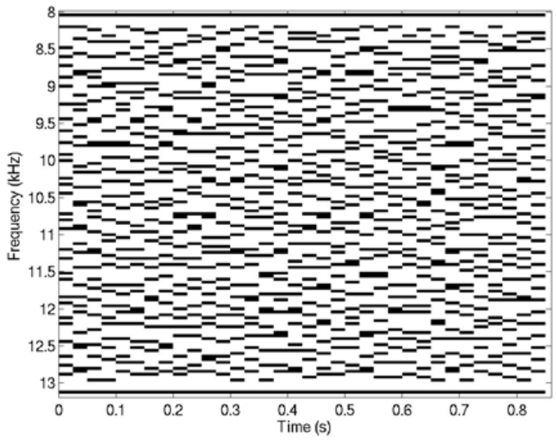

Fig. 5. Spectrogram of a 2400 bps MFSK transmission. Black regions indicate the tone is on and white regions are off. Pilot tones are at 8 and 13.2 kHz.

Preceding the MFSK transmissions is an m-sequence that is used to determine the signal start. To decode the data, the receptions are matched filtered (with the replica m-sequence) to acquire the start of the signal and frame the MFSK transmission. A spectrogram is then taken of the MFSK portion of the time series using a non-overlapping boxcar window of 25-ms duration. The highest tone in each of blocks of 4 tones is then determined. A sample reception of a 2400 bps transmission is shown in Fig. 6. This is for receptions at about 4-km from the source in the Ship Island and La Jolla experiments. For Ship Island, the signal-to-noise ratio (SNR) is about 5 dB while it is 20 dB for La Jolla. Note that for the Ship Island data most of the on-tones are recognizable in comparison with Fig. 5 (although some at the higher frequencies are slightly “washed-out”). The La Jolla data has much higher signal to noise ratio, but the individual on-tones are not nearly as recognizable as for Ship Island.

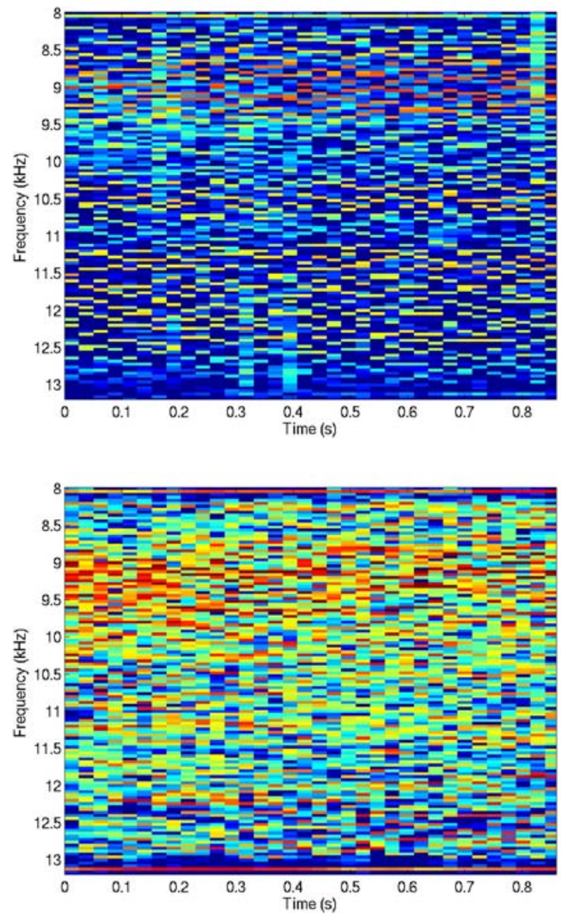

Fig. 6. Spectrograms of 2400 bps MFSK receptions for the Ship Island (top) and La Jolla (bottom) experimental sites. In both cases, the receiver is about 4-km from the source, for Ship Island the signal to noise ratio is about 5 dB and for La Jolla about 20 dB. Both plots use a relative scale in dB with colors spanning a 15 dB dynamic range.

The differences in receptions from the sites are apparent when comparing bit errors and this is shown in Fig. 7 for the 3 sites. The plots are shown as bit error rates versus SNR and illustrates how large signal-to-noise ratios do not always give low bit errors. Note, in Fig. 7 the Ship Island data has much lower bit errors even for significantly lower SNR. This is consistent with the spectrograms in Fig. 6 that show high SNR for La Jolla but at the same time a much greater blurring of the tones. These differences are mostly due to the multipath characteristics and in the next section, propagation modeling is used to simulate this.

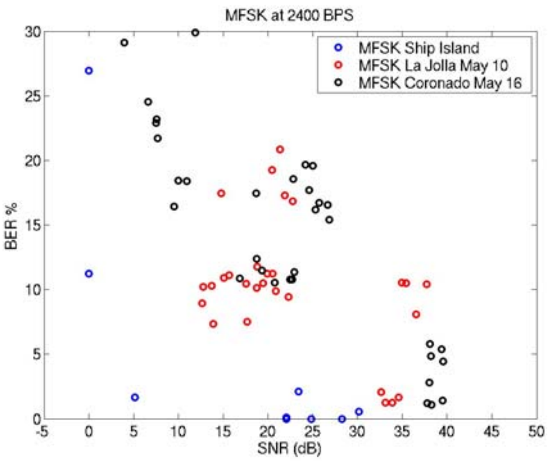

Fig. 7. Bit error rate as a function of signal to noise ratio for 2400 bits/s MFSK at the 3 experimental sites. Note, the Ship Island data has far fewer bit errors even for low signal to noise ratio.

IV. MODELING THE CHANNEL

A. Modeling the Impulse Response

There are obvious differences in MFSK performance at the 3 experimental sites considered as discussed in the previous section and illustrated in Fig 7. Acoustic modeling is valuable to determine to what extent performance is driven by SNR as compared with environmental factors causing multipath arrivals. The modeling strategy is to use the Bellhop Gaussian Beam model to determine the channel impulse response [6]. These modeled impulse responses will be compared with those measured using the transmitted acoustic probes (LFM's). Once a satisfactory model is developed, the communications signals are simulated and compared with measurements. Systematically, various environmental parameters and/or signal to noise ratio can be varied.

The Bellhop output is a set of complex arrival amplitudes and arrival times. Assuming no frequency dependence, these arrivals represent the impulse response of the channel. To compare with the measured probe signals, the arrivals time-series is calculated for the same set of source/receiver geometries (e.g. ranges) and convolved with the LFM replicas to produce the simulated impulse response. The water column sound speed profile was measured and was used in all the simulations. However, the seabed and exact source/receiver geometry was less well know. These unknowns were determined through an inversion process based on a genetic algorithm, global optimization.

The global optimization for unknown parameters involves several components. 1) The unknown parameters and their search space are defined. In this case the unknowns were seabed sound speed, density and attenuation, the source and receiver depths and the source/receiver separation. 2) Since the search space can be very large even for just a handful of parameters an efficient search algorithm is needed. Here, a genetic algorithm global search method was used. 3) A cost function is defined to compare the measured with simulated data. Here, the magnitudes of the measured and simulated envelopes were correlated and the maximum value indicated the degree of agreement. The best fit from all the genetic algorithm populations was the assumed value for the unknown parameters. The resulting, simulated impulse response functions for Ship Island and La Jolla sites are shown in Fig. 8.

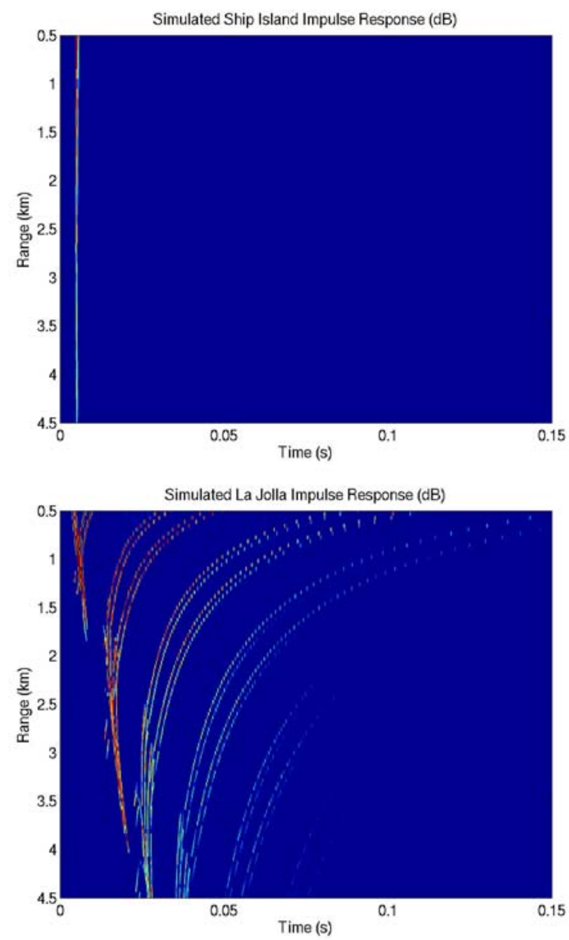

Fig. 8. Modeled impulse response envelopes for SX-E and SX-F sites. Top panel shows results for SX-E Ship Island, lower panel is for SX-F La Jolla.

In general, the modeled impulse response functions are in agreement with those measured. There are, however, some differences. The most obvious is the larger time-spread for the individual measured arrivals compared to the model. These differences are likely caused by several factors. First, the measured data represents an average of many impulse response envelopes and each of these can have slightly different arrival patterns that depend on the time-varying nature of the channel (e.g. sea-surface). This is not modeled and therefore only a single distinct arrival shows up for each path. In the measured data at both sites there is a scatter and reverberation tail that is not modeled properly

since the ray trace is assuming specular reflections and neglecting backward propagating energy. The extent this impacts communications is not entirely clear but it does increase the background noise level. Another difference is the disappearance of the first arrivals at a shorter range in the model compared to the measurements. This disappearance of arrivals can easily be caused by slight differences in the water column sound speed profile. In the model a representative profile was used and this will likely differ somewhat from the actual profile on the acoustic track due to time and space variations. However, once the geometry and seabed properties are determined, the main features of the multipath are captured in the simulations for the different sites. Source/receiver geometry and seabed properties are the parameters that dominate the character of the impulse responses.

B. Modeling the MFSK signals

The MFSK transmissions can also be convolved with the modeled impulse response functions to simulate the communications performance. The modeled spectrograms are shown in Fig. 9 for the Ship Island (top panel) and La Jolla (middle panel) sites. The modeled MFSK spectrograms can be compared with the measurements shown in Fig. 6. In these simulations no noise has been added and the impact of the multipath is isolated and can be seen in Fig 9. In the top panel, the Ship Island data looks very similar to the measurements and the transmission pattern is recognizable. In the middle panel, the La Jolla data also looks similar to the measured spectrogram and the impact of the multipath is evident. The lower panel in Fig. 9 shows the simulation result for the La Jolla site but with the seabed properties taken from the much lossier Ship Island site. In that case, the role of the seabed is clear- as the MFSK pattern is much more clearly recognizable (the multipath has nearly disappeared). For the simulated data in Fig. 9, the Ship Island results had no bit errors while the La Jolla simulation gave 2.2 percent bit errors. For the artificial case shown in the lower panel in Fig. 9, the errors were again 0.

IV. DISCUSSION AND CONCLUSION

For communications signals there have been few experiments with simultaneous acoustic and environmental measurements so that comparisons can be made between measured and simulated data using physics based modeling. In many cases with model/data comparisons, the channel model contains a few arrivals that are given a randomized phase. However, in the examples shown here, the nature of the multipath is extremely important and requires modeling include the geometry, water column and seabed properties. Examples are given here of the importance of proper modeling as the seabed properties greatly influence the characteristics of the multipath and therefore bit errors. The approach taken is to first fine-tune the acoustic model- optimizing over unknown parameters using measured environmental and acoustic measurements. Once a satisfactory model is developed the communications signals are simulated. Trends in the bit errors matched the measured data, however, because of some of the simplifying assumptions the simulations showed much fewer bit errors. Follow-on work will improve the model and include time-evolving properties of the channel such as the rough sea-surface.

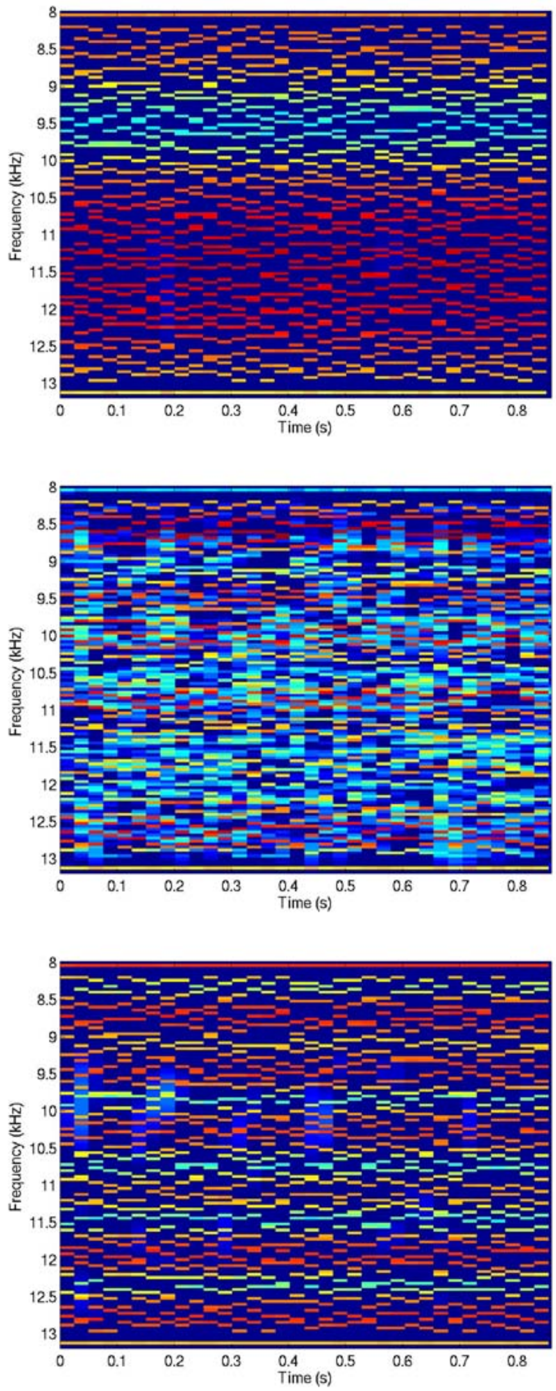

Fig. 9. Spectrograms of simulated 2400 bps MFSK receptions for the Ship Island (top) and La Jolla (middle) experimental sites. The bottom panel shows the La Jolla site with a seabed similar to that at Ship Island. In all cases, the receiver is about 4-km from the source, and there is no added noise. The plots use a relative scale in dB with colors spanning a 15 dB dynamic range.

REFERENCES

[1] C. Bjerrum-Niese, L. Bjorno, M. Pinto and B. Quellec, “A Simulation Tool for High Data-Rate Acoustic Communication in a Shallow-Water, Time-Varying Channel”, *IEEE J. Oceanic Eng*., Vol. 21, No. 2, April 1996.

[2] D. Kilfoyle and A. Baggeroer, “The State of the Art in Underwater Acoustic Telemetry”, *IEEE J. Oceanic Eng*., Vol. 25, No. 1, January 2000.

[3] APL-UW *High-Frequency Ocean Environmental Acoustic Models Handbook*, APL-UW TR9407 (1994).

[4] V. K. McDonald, J.A. Rice, Michael B. Porter, Paul A. Baxley, "Performance measurements of a diverse collection of undersea, acoustic, communication signals", *Proceedings of IEEE Oceans 1999*.

[5] Michael B. Porter, Vincent McDonald, Joseph Rice, Paul Baxley, “SignalEx: Linking environmental acoustics with the signaling schemes” *Proceedings of IEEE Oceans 2000*.

[6] F. Jensen, W. Kuperman, M. Porter and H. Schmidt, *Computational Ocean Acoustics*, (second edition) Springer-Verlag (2000).

.